Machinery Messages

Case History

The root cause of a shaft crack

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A Bently Nevada online diagnostic system provided data that convinced maintenance personnel at an Australian ammonia plant that a shaft crack might be occurring on a critical syn gas compressor train. The incident occurred in October 1991. Data showed a sudden and dramatic change in 2X amplitude and phase. It subsequently proved to be very accurate, and the shutdown of the machine saved it from a potentially catastro-phic failure.

A comprehensive investigation by plant personnel, with the assistance of Bently Nevada machinery diagnostic and alignment specialists, eventually identified the root cause of the problem. The corrective action taken as a result of this investigation removed major plant bottlenecks, and ensured that the problem would not recur.

Shaft crack shuts down plant

The machine, a synthesis gas compressor (Figure 1), is used to make ammonia at Incitec's Gibson Island Works, in Brisbane, Australia. Incitec is the largest supplier of fertilizers and industrial chemicals in Australia, and ammonia is the principal chemical required for the manufacture of these products. Therefore, the gas compressor is the most critical machine in the plant.

In 1985, the ammonia plant was uprated to 120% of the original design capacity, to approximately 635,000 kg (700 tons) per day. However, during recommissioning, severe problems occurred with the speed increasing gearbox of the synthesis gas compressor. These problems were so severe that extensive gearbox structural and internal mechanical modifications were required before reliable operation was achieved in 1987. Even after the modifications, the ammonia plant still couldn't operate continuously at 120% capacity. This was due to elevated temperatures on the high speed pinion output shaft coupling end radial bearing (known onsite as the "northwest bearing").

Previous experience had shown that temperatures in excess of 121°C (250°F) would result in the rapid failure of the northwest bearing, and therefore, an alarm was configured to warn plant operators when this temperature was reached. When the temperature monitor went into alarm, operators immediately reduced plant production until the bearing temperature stabilized at a lower temperature. This problem with the northwest bearing effectively limited the entire plant production to 115% of capacity.

Often, the plant would run at 120% plant capacity for several weeks, with the northwest bearing temperature at 117°C (243°F). Then, the bearing temperature would suddenly rise, in a step-like manner, forcing operators to reduce production until the bearing cooled. Often, production would have to be reduced to 112% before the bearing's temperature became stable.

In October 1991, information from an online Bently Nevada Dynamic Data Manager® System suggested that a crack might be propagating on the input shaft of the speed increasing gearbox. Maintenance personnel advised that the syn gas compressor be shut down immediately, which stopped the ammonia plant and downstream production. Upon disassembly, maintenance technicians found that the input shaft coupling taper was cracked, 180 degrees around its circumference and through 55% of its diameter (see photo pg.21).

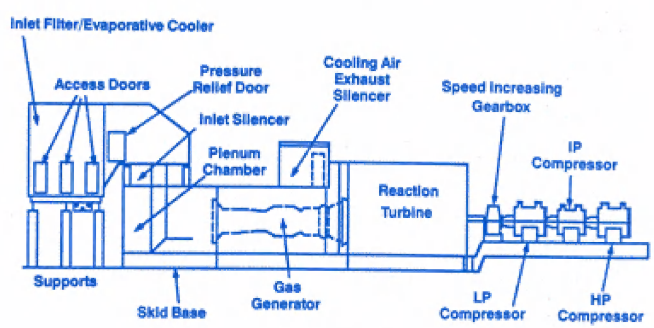

Figure 1

The Synthesis Gas Compressor train is unusual. It does not use a steam turbine driver. Instead, it is driven by a gas generator exhausting into a reaction turbine. The reaction turbine drives three "barrel type" compressors, through a speed-increasing gearbox.

A spare set of gears was installed, and the machine returned to service. The September 1992 issue of *Orbit* describes how the cracked shaft was detected, and the compressor saved.

Investigating the shaft crack

The failed gears were of high quality, and had been in service for less than four years. To understand why the shaft cracked, and to prevent it from recurring, Incitec began an in-depth investigation of the problem.

Incitec commissioned a failure analysis of the input shaft that included fractography, chemical analysis, metallurgical examination and hardness testing. Fractographic analysis of the damaged shaft showed that the crack had begun adjacent to the coupling taper keyway, where fretting and corrosion damage was evident. The crack had slowly spread, radially and against the direction of rotation, into the coupling taper keyway. Then, it reversed direction and spread rapidly in the direction of rotation. Failure analysis concluded that the shaft cracked due to fatigue.

Next, Incitec reviewed trend and alarm data from their Bently Nevada Dynamic Data Manager® System (DDM). DDM is a permanently-installed online diagnostic system for critical machinery. It automatically collects and stores data during steady state machine operation, at predefined intervals and whenever an alarm occurs. DDM data is essential for localizing machine problems and for

understanding how they developed. Incitec later upgraded their DDM System to the Bently Nevada Transient Data Manager® 2 System (TDM2). TDM2 is more powerful than the DDM System, because it is not limited to steady-state data. It acquires data during transient machine operation, when a machine changes speed or load. Transient data acquired during machine startups and shutdowns reveals fundamental machine characteristics that steady-state data cannot.

The DDM trends of thrust position showed unusual axial movement of both the gearbox input shaft and the reaction turbine rotor. These trends indicated that the reaction turbine rotor would periodically move away from the gearbox and toward the gas generator, at the same time as the gearbox input shaft moved away from the reaction turbine. Thrust bearing temperature changes, on both shafts, confirmed the thrust trend data.

Trend data showed that the unusual axial motion was not constant, but instead followed a 24-hour cycle. During the day, the gearbox input shaft and reaction turbine rotor would move away from each other, then at night, the movements would reverse. Also, by correlating shaft axial motion with ammonia plant production, it became clear that unusually large shaft axial movements corresponded with changes in ammonia production, to keep the northwest bearing temperature under 121°C (250°F).

Old gearsets were also examined. One gearset, thought to have been removed from the synthesis gas compressor gearbox in the 1970s, had a crack on its input shaft coupling taper that was identical in size and location to the one being investigated.

Misalignment is suspected

The investigation concluded that the crack on the input shaft was probably due to severe misalignment between the reaction turbine and the gearbox, for these reasons:

- Misalignment could produce the cyclic forces necessary to cause fatigue failure. The corrosion observed near the keyway, where the crack began, was probably caused by an imperfect coupling fit.
- Misalignment could cause the

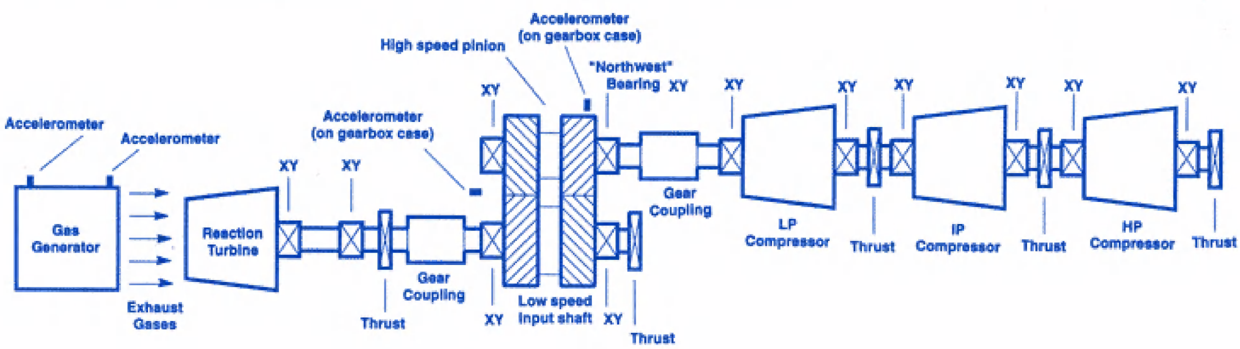

Figure 2

Machine train diagram showing transducer placement.

flexible gear-type coupling between the two units to "lock-up," which could cause the unusual axial movements observed on both the gearbox input shaft and the reaction turbine rotor.

The second cracked shaft indicated that, if the turbine and gearbox were misaligned, they had been misaligned for a long time. Investigators believed that the problem worsened after the Synthesis Gas Compressor's speed and load were increased in 1985 to accommodate increased production requirements.

The investigation also indicated a strong relationship between the suspected misalignment and the northwest bearing's high temperature. However, the exact nature of the relationship was not clear.

Accurate thermal offsets required

The Synthesis Gas Compressor train had traditionally been aligned using thermal offsets that had evolved over time. The Original Equipment Manufacturer's (OEM) manual suggested establishing a thermal offset by first running the machine train up to full operating load and temperature, then quickly stopping it and checking the coupling alignment. From past measurements, technicians had developed cold alignment settings that they applied each time the machine train was aligned. The reaction turbine rotor had been cold-aligned using those offsets, at 0.5mm (0.020 inches) lower than the gearbox input shaft.

This time, plant personnel wanted a more accurate thermal offset measurement. They decided to measure the position of the reaction turbine casing relative to the gearbox frame, both when the machines were cold and when they were at operating temperature. They would use that information to calculate the hot coupling alignment, and the severity of the suspected misalignment. From this, they could develop more accurate cold coupling alignment targets to compensate for the different thermal growths of the two machines. Plant personnel also wanted to measure the difference in thermal growth between the gearbox and the LP compressor, to determine if misalignment was causing the northwest bearing to overheat.

Measurement techniques

Two measurement systems were accurate enough to make those measurements. One was a laser system and the other was Bently Nevada's optical system. In the laser system, laser-emitter/sensors are mounted on one side of the coupling, on both the horizontal and vertical centerlines. Reflecting prisms are mounted opposite the sensors, on the other side of the coupling. When the machines are cold, the lasers are adjusted so the beams reflect from the prism to the center of the laser. Then, as the machines reach operating temperature, the position of the laser beam on the sensor indicates the difference in the thermal growths of the machines.

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The Bently Nevada optical system is a highly-accurate derivative of surveying equipment. It uses scales attached to the vertical and horizontal centerlines of the machines, and a special optical telescope. Operators measure the positions of the machines by viewing the scales through the optical telescope. With this information, they map the position of the machines relative to each other, both when cold and at operating temperature.

Incitec chose the laser system, because they hoped to solve the problem in-house, while developing expertise that would help solve other alignment problems.

Calculating the correct offset

Incitec purchased the laser equipment in late 1992. They shut down the synthesis gas compressor in January 1993 for two days, to modify the machine, so the laser equipment could be installed. A representative of the laser equipment vendor was present during the machine outage, to ensure that the equipment was properly installed and the data correctly interpreted.

It was relatively easy to mount the lasers and prisms on the gearbox and the LP compressor. However, it was difficult to mount the reflecting prisms in the bearing tunnel of the reaction turbine, due to restricted access and heat from exhaust gas leakage. In fact, both the laser sensors and the prisms had to be water-cooled to ensure reliable operation.

Laser equipment measurements showed severe misalignment between the reaction turbine and the gearbox, and slight misalignment between the gearbox and the LP compressor. From these measurements, plant technicians prepared offset targets to use in aligning the compressor train after the overhaul. The overhaul was scheduled during a major shutdown of the ammonia plant, in February, 1993.

Alignment is unsuccessful

The Synthesis Gas Compressor was overhauled and the machine train realigned to the prepared offsets. However, during recommissioning, vibration amplitudes on the reaction turbine were so severe, even at minimum operating speed, that the startup had to be terminated.

Plant personnel reviewed Transient Data Manager® 2 data collected during the unit's startup. It showed that the reaction turbine and gearbox were grossly misaligned, from which technicians concluded that the offset targets

had been wrong. Plant personnel had no time to measure the hot alignment. Instead, they reduced the vertical offset between the two units by 0.38 mm (0.015 inches).

When the machine was restarted the following afternoon, vibration levels had dropped, but were still much higher than before the shutdown. Incitec contacted Bently Nevada's Machinery Diagnostic Services (MDS), which reviewed the TDM2 data via a modem connection. Bently Nevada engineers determined that the machine train could be safely operated for a short time, so plant production could continue while the problem was reanalyzed. However, the temperature of the gearbox "northwest" bearing was also much higher than before the shutdown. To keep the bearing temperature below 121°C (250°F), operators had to limit plant production to 104%.

Further investigation

Obviously, the reaction turbine, gearbox and LP compressor had not been correctly aligned. This was clearly shown in TDM2 average shaft centerline position plots, of the gearbox "northwest" bearing and the LP compressor drive-end bearing.

In a machine with fluid-film bearings, such as this, the rotor normally rises on an oil wedge as it gains speed. At operating speed, a shaft rotating Y to X (cw) with no abnormal load will usually be in the lower left quadrant of its bearing. It is clear from Figures 3 and 4 that the rotor is abnormally loaded, because of the atypical operating positions.

Incitec wanted to learn why the realignment had failed, and then correctly align the machine train, in the shortest possible time, while maximizing ammonia production. Plant personnel decided to repeat the thermal growth measurements, this time using both laser alignment and Bently Nevada's optical system.

The laser equipment vendor's representative returned, and a Bently Nevada alignment specialist joined him, to take optical measurements. At the end of April, both systems were used to take measurements while the machine was hot. Then, the unit was shut down and allowed to cool for approximately eight hours, and another set of measurements was made. The machine was restarted, brought up to maximum load, and a final set of measurements was taken.

Plots from the laser and the optical data both showed gross radial and axial misalignment, between the reaction turbine and the gearbox pinion. Both also showed misalignment between the gearbox high speed pinion and the LP compressor. However, the optical data also showed something not evident in the laser data, that the gearbox had moved sideways when the machine was restarted.

Technicians believed that the unexpected sideways movement of the gearbox was caused by the forces due to misalignment, especially since the gearbox casing had never been doweled to its pedestal.

Optical measurements were then used to calculate the alignment targets. The targets provided a cold shaft offset that yielded optimum alignment when the train was operating.

Realignment

The alignment work was completed on schedule in June 1993. A Bently Nevada alignment specialist was onsite to provide advice and to perform another optical survey after the machine was restarted.

When the machine restarted, vibration levels were much lower than they had been prior to the February 1993 shutdown. At first, the plant operated at 118% of original capacity. The Bently Nevada alignment specialist conducted a full optical survey of the machine train. The alignment was acceptable, except for the horizontal alignment between the IP and HP compressors. However, as plant production increased, the gearbox northwest bearing again became hot, and again limited plant production, to 99%.

Gearbox flexing

It was clear that misalignment was not causing the northwest bearing to overheat, and plant personnel discussed other possible causes, including the lack of gearbox rigidity. In 1987, a large hole had been cut in the bottom of the gearbox casing, to improve drainage. According to this theory, the gearbox casing was flexing

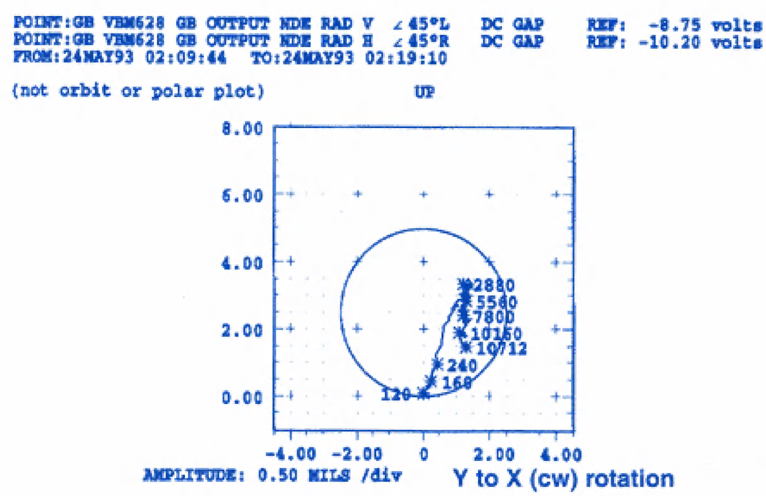

Figure 3

Shaft centerline plot, showing movement of the gearbox high speed pinion in the "north west bearing" during machine startup.

under load, "edge loading" and overheating the northwest bearing.

Various techniques were considered for measuring gearbox flex, one of which was to install strain gages on the entire casing. However, it was decided that an optical survey would be more accurate and cost-effective.

Plant personnel again shut down the synthesis gas compressor train. Technicians installed measurement scales on the horizontal and vertical centerlines of the high and low speed shafts, and on the base of the gearbox and its pedestal support. This time, the machine train would be mapped out completely. Technicians made a full set of measurements while the Synthesis Gas Compressor was at operating temperature, before it was shut down. Measurements were taken again after the unit had cooled, but before the gearbox cover was removed. A third set of measurements was taken after the gearbox had been inspected and its cover replaced, to ensure that the cover was reinstalled correctly. A fourth set of readings was taken after the unit was back online.

Each set of measurements showed that all gearbox movement was due to thermal growth, and that neither the gearbox casing nor its pedestal support had flexed under load.

The root cause

The root cause was revealed when the gearbox was inspected. Inspection showed that both high speed pinion radial bearings were edge-loaded. However, gearbox flexing was not the cause. Marks on the bearings indicated that the pinion was deflecting downward under load, placing all of its load on less than 25% of the bearing babbitt area.

In previous inspections of the gearbox, the pinion's load was evenly distributed on both bearings, although the northwest bearing was heavily loaded. A new, finite element analysis of the high speed pinion determined that the gear area was quite rigid. However, it also showed that the journals were deflecting 0.04 mm (0.0015 inches) under load.

Plant personnel concluded that misalignment between the gearbox and the LP compressor had forced the journal out of its natural shape when it was loaded. Now that the misalignment was corrected, the bearing's load was less, but was concentrated in a smaller area. That is why the northwest bearing was even hotter after the machine was aligned.

Measurements showed that, when the high speed pinion was cold, the bearing journals were true to the radial bearings. Technicians placed 0.04 mm shims under the inner edge of the bearings, to make them tilt upward. Then, they scraped the bearings until there was even contact across the babbitt.

Before restarting the Synthesis Gas Compressor, the shims were removed. Without the shims, the outer edges of the radial bearings should be loaded at low loads, which should cause higher operating temperatures. However, at full load, when the journals deflected, the load distribution should improve.

Indeed, when the Synthesis Gas Compressor was restarted, at low load both of the high speed pinion bearings were approximately 7°C (20°F) hotter than before. However, as load increased, the temperatures stabilized, and a full load of 120% was achieved. The northwest bearing temperature never exceeded 110°C (230°F).

Conclusions

The problems with the Synthesis Gas Compressor were complex and interrelated. However, these conclusions can be made:

- Accurate measurements are essential. This problem would not have been solved without accurate equipment for monitoring, trending and diagnosing machine vibration, as well as measurement of static and dynamic alignment.
- Strong support from management is essential in solving complex problems, particularly when carefully prepared plans go wrong.
- Even the most experienced plant engineers sometimes require help in solving complex problems.

Bently Nevada's TDM2 system, along with knowledgeable diagnostic and alignment specialists, provided essential information and advice that helped Incitec technicians solve this difficult problem. Bently Nevada's expertise is available worldwide, to help solve complex problems and keep plants running. Contact your nearest office for more information.

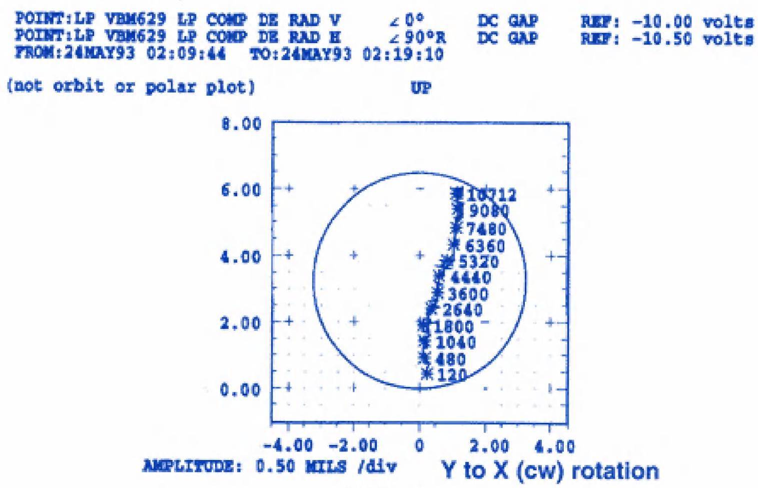

Figure 4

Shaft centerline plot, showing the shaft movement at the drive end bearing of the LP compressor during machine startup.